LINEAR ENERGY TRANSFER SPECTRUM OF PROTON EXPOSURE ON MERCURY MISSION MA-9

Hermann J. Schaefer

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LINEAR ENERGY TRANSFER SPECTRUM OF PROTON

EXPOSURE ON MERCURY MISSION MA-9

Hermann J. Schaefer

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Approved by

Captain Ashton Graybiel, MC USN
Director of Research

Released by

Captain Clifford P. Phoebus, MC USN
Commanding Officer

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SUMMARY PAGE

THE PROBLEM

The energy spectrum of the astronaut's proton exposure in the South Atlantic Anomaly on Mercury Mission MA-9 presented in an earlier report lends itself to a differential analysis of absorbed dose with separate determination of the fractional dose produced at a high Linear Energy Transfer (LET). This fraction can be expressed in terms of Relative Biological Effectiveness (RBE) and Quality Factor (QF) as defined by the RBE Committee to the International Commission on Radiological Protection (ICRP), or in terms of the differential LET spectrum. The results of both approaches are presented.

FINDINGS

The high LET dose fraction is exclusively due to protons in the energy interval below 1.0 Mev. In this critical region, RBE and QF as well as differential particle flux show extremely steep changes in their dependence on energy. As a consequence, small errors in the flux values appear substantially magnified in the dose equivalents. Experimentally the flux values in the critical energy region are obtained from counting "enders," i.e., protons reaching the end of their ionization ranges. In degraded continuous energy spectra such as the one for the proton exposure on MA-9, the ratio of enders to total flux is always very small. Indirect determination of the fractional doses of high RBE and QF from data on the energy spectrum, therefore, is a method of sharply limited accuracy.

The alternate method of establishing the differential LET spectrum suffers essentially from the same shortcoming. It does have the advantage of bypassing the problematic issue of RBE and QF since it limits itself to the physical parameters in which a radiation differs from standard x-rays. The LET spectrum of the proton exposure on MA-9 shows a configuration basically similar to that of standard x-rays, yet reaching out, at both ends of the LET scale, to lower and higher LET values, respectively. The spectrum closely resembles those established in earlier studies for the energy spectra of solar particle beams obtained in instrumented balloon and rocket flights.

The results indicate that dosimetric instrumentation for measuring both absorbed dose and RBE or QF dose equivalent of the astronaut cannot use the method of singling out the fractional high LET dose by analyzing residual ranges. Because of the extremely short track segments on which LET passes through a sharp maximum, these ionization "spikes" should be measured directly and separately.

INTRODUCTION

In a preceding report (1), hereafter referred to as Report 27, the results of radiation measurements with nuclear emulsions on Mercury Missions MA-8 and MA-9 have been reported. For Mission MA-9 in particular, the energy spectrum of the proton flux penetrating the emulsions was established by track and grain counting and was evaluated in terms of absorbed dose. For the entire thirty-five hour mission of 22 orbits, an integral dose of 27 millirads was obtained for the proton component. By establishing fractional doses for small intervals of the differential energy spectrum and applying to each fraction the appropriate values for relative biological effectiveness (RBE) and quality factor (QF) according to the formulae of the RBE Committee to the ICRP (2), the dose equivalents also were assessed. An RBE dose equivalent of 31 rems and a QF dose equivalent of 41 rems were found.

Establishing dose equivalents of a proton exposure in the indicated way is an entirely acceptable procedure if the official exposure status of the astronaut is of interest. From a scientific standpoint, however, RBE and QF are rather unsatisfactory quantities since a number of arbitrary limitations and specifications are contained in their definitions. An alternate way of describing those physical characteristics of a radiation, which are responsible for its biological effectiveness, is the analysis of the LET spectrum. The details of how the LET spectrum of a heterogeneous proton radiation can be derived from the energy spectrum have been discussed in an earlier report (3). In the same paper, the local LET spectrum as it would develop in tissue exposed to a typical flare produced proton beam was derived theoretically. It seems of interest to apply the same analysis to the energy spectrum of the proton exposure on Mission MA-9 as it was recorded in the capsule behind a combined shielding equivalent to that surrounding the astronaut himself. The present report presents the results of this analysis. In addition, it examines the limitations of the method of evaluation that make themselves felt for spectra in which the high LET section represents only a small fraction of the total energy dissipation.

SIGNIFICANCE OF "ENDERS" FOR ASSESSING PROTON DOSE EQUIVALENTS

The LET of a proton assumes values greatly exceeding those of standard x-rays only on the last 50 micra of its path in tissue corresponding to a residual kinetic energy of about 1.5 Mev. The fractional energy dissipation on this terminal portion of a proton track in tissue represents that part of the total absorbed dose to which an RBE substantially larger than for standard x-rays has to be assigned. In terms of the differential energy spectrum of the proton exposure on MA-9, which was shown in Figure 5 of Report 27 and is reproduced here for the reader's convenience in Figure 1, this dose fraction is compressed into the narrow interval from zero to about 1.5 Mev on the abscissa scale. It is seen that this particular section of the spectrum shows an extremely steep positive slope. In this same energy interval the so-called Bragg peak of the LET

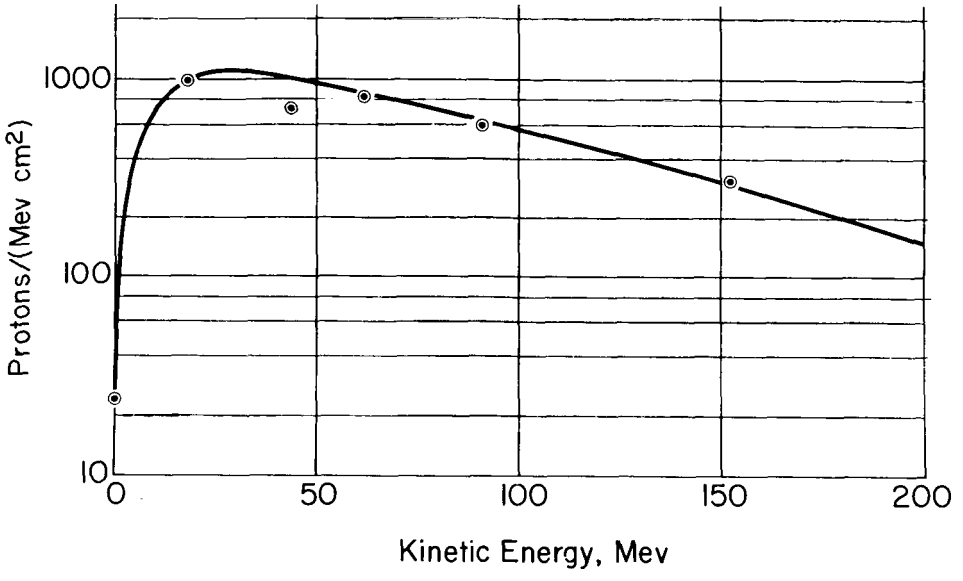

Figure 1

Differential Energy Spectrum of Proton Exposure on
Mercury Mission MA-9

occurs, and the LET changes very steeply and in a nonlinear fashion with energy. In fact, this change is so strong that an accurate analysis would require a breakdown of the abscissa scale, in this particular region close to zero, into classes of only 0.005 Mev width or preferably even less if representative mean LET values for each class are to be used. It needs no further explanation that, because of these strong functional dependences among energy, range, and LET, a minor experimental error in the configuration of the differential energy spectrum would appear greatly magnified in the corresponding dose fraction. This points out the need for a thorough examination of the accuracy with which the point at zero energy and the initial steep rise of the differential energy spectrum are determined experimentally.

As long as interest is limited to the total absorbed dose in millirads, a deficient accuracy at the low energy end of the spectrum is of no practical importance. As is seen from Figure 1, the differential flux in the critical energy interval close to zero is much smaller than at medium and high energies. Therefore, the contribution of this interval to the total dose is also much smaller, and even a major systematic error would influence the total dose only slightly. If, however, a separate assessment of the high LET fraction of the total dose is of interest, any error in the indicated energy interval will fully show up in the result and will even be magnified further since this particular dose fraction has to be assigned a high RBE or QF factor.

At this point it should be remembered that the fractional high LET dose is of special significance for the determination of the low-dose rate, long-term damage from accumulated exposures over longer time intervals because experimental evidence indicates that such damage shows little or no recovery, contrary to damage from normal low LET radiation for which official recommendations (4) allow a recovery factor of 2.5 per cent per day. It is seen, then, that the high LET fraction of a proton exposure of an energy spectrum of the type of Figure 1, despite its relative smallness as compared to the total dose, eventually will constitute the main contribution to the lifetime dose of an astronaut. This fact indicates the need for accurate measurement of this dose fraction even though it would not be a significant factor in a one-time acute exposure, such as could occur in a major flare event.

It was shown above that the high LET dose fraction originates exclusively from protons coming to rest in tissue. It is obvious that, for a spectrum of the configuration shown in Figure 1, the enders constitute only a very small fraction of the total flux. If we examine a parallel beam of protons entering a plane layer of tissue of 200 micra thickness from the left as indicated in the right hand sketches of Figure 2, we can visualize, in a conceptual experiment, the entering protons arranged in order of their residual ranges. This would lead to a geometrical array as shown in the same figure. To be sure, these sketches show only the particles at the low energy end of the total array. For a complete account, a much larger number of "through shots" would have to be indicated. In the present context, however, only the enders are of interest. If we assume that the enders are distributed evenly throughout the tissue layer, we would obtain, in the ordered arrangement, a straight line contour as indicated in the upper right hand sketch of Figure 2. Depending on spectral configuration, however, the number of enders per unit volume can vary with depth. For instance, it could show a negative gradient; i.e., it could decrease with increasing depth as indicated in the lower right hand sketch of Figure 2.

If the two cases in Figure 2 are described in terms of the flux/depth and flux/energy functions, the plots of the two left hand graphs are obtained. The case of even distribution with a depth gradient of zero corresponding to a straight line contour of the endpoints is marked "R linear"; the case of uneven distribution with a negative depth gradient is marked "E linear." The reason a linear flux/depth function leads to a nonlinear flux/energy function and vice versa rests in the strongly nonlinear range/energy function that governs the terminal section of a proton track.

It is seen by inspection that, for the same mean number of enders in the 200 micra layer, the local dose in the first few micra is substantially larger for the linear flux/energy function than for the linear flux/depth function. An experimental evaluation, which would establish only the mean number of enders per 200 micra tissue, would not furnish any clues on the actually existing configuration. The true maximum dose, therefore, could not be established, but merely the mean dose, unless additional information concerning the depth gradient is furnished. It is easily seen from the plots in Figure 2 that, for such additional information, statistical significance would have to be

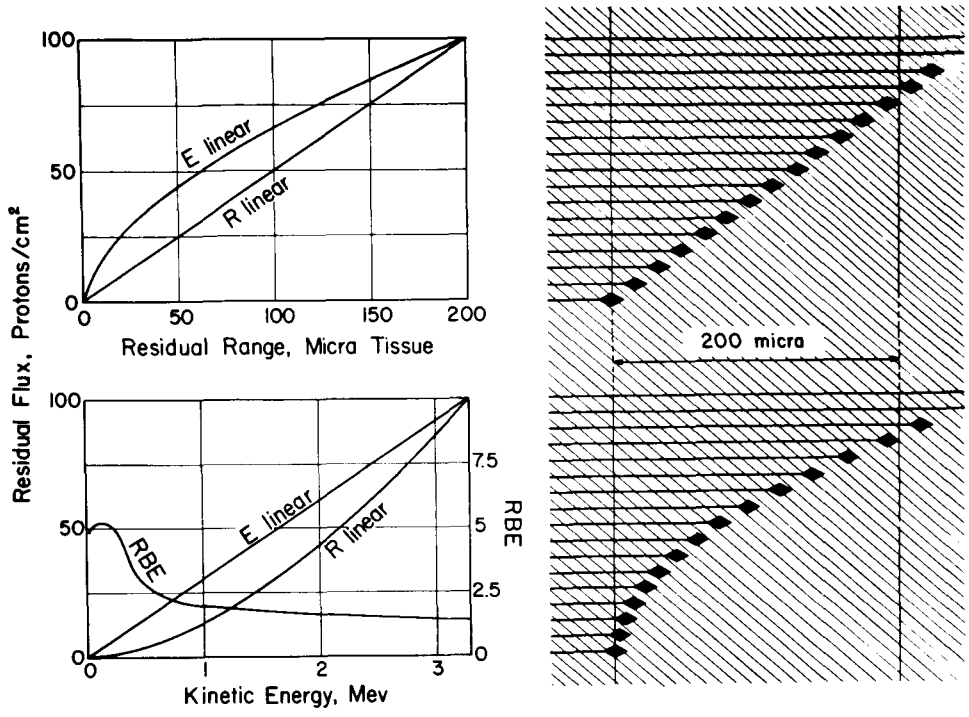

Figure 2

Distribution of "Enders" in Tissue Bombarded by a Parallel Beam of Protons with Continuous Energy Spectrum

Upper right: Distribution "linear in R" as it would normally develop for a continuous energy spectrum degraded by absorption. Lower right: Fictitious distribution "linear in E" as it could develop only from special discontinuities in the configuration of shielding or the incident spectrum.

established separately for the enders count in individual consecutive layers as thin as a few micra throughout the entire depth of the 200 micra tissue layer. Since such measurements normally would be attempted with nuclear emulsions, the conditions are still more stringent because of the greater stopping power of emulsion. If a stopping power ratio emulsion to tissue of 2.33 is assumed, a 200 micra tissue layer would be equivalent to an emulsion layer of 86 micra.

The indicated difficulty in determining the high LET fraction of the total dose is of a basic and general nature because the local flux for any degraded continuous proton spectrum will always show a very small ratio of enders to total flux. For omnidirectional incidence of the radiation, the geometrical relationships become more complex and spectral degradation is different for different directions. For the

case of the earth's atmosphere in particular, the ratio of enders to vertical flux is an important magnitude for inferences on the energy spectrum of the incident beam outside the atmosphere and constitutes the main limitation of accuracy in its determination. These aspects have been discussed by Ney and Stein (5).

If an incident beam of protons with a continuous energy spectrum is attenuated by a more or less uniform shielding layer, analysis of the spectral transition shows that the low energy end of the degraded spectrum will be very nearly linear in R; i.e., the depth gradient of the enders count will be very nearly zero. If, however, the shield material is unevenly distributed, producing abrupt directional cut-off effects in the local flux, large gradients of the enders count will prevail in certain directions, yet will remain hidden behind the statistical fluctuations of the local enders count unless very large emulsion volumes are used. It stands to reason that inside a Mercury capsule the directional shielding of vehicle frame and equipment exhibits a highly structured pattern, producing irregular discontinuities in the spectrum of the residual beam. To identify these with the enders count in a small emulsion pack for a total absorbed dose of only 27 millirads is a hopeless undertaking, though the grand total of the enders count offers a very satisfactory accuracy for determination of the energy dissipated at a high LET in the total emulsion volume scanned.

The problem of directional inhomogeneities of the local flux in the emulsion pack is not limited to enders. The aforementioned great complexity in the distribution of absorbing matter around the emulsion pack and the astronaut can be expected to make itself felt up to higher energies in the spectrum. Here again, however, one should distinguish clearly between determination of dose and LET distribution, on the one hand, and analysis of the directional composition of the local flux, on the other. The former can be established with any desired accuracy if the total track length in a given volume and the LET distribution along this total length are known. The latter, of great interest for the physicist seeking information on the composition of the incident beam, requires much more complex evaluation procedures in scanning the emulsions.

In this connection, it seems of interest to discuss the meaning of the term protons/cm^2 which appears in the ordinate units of the differential energy spectrum in Figure 1. If, for a given volume of emulsion or tissue, the combined total track length of the proton population expressed in cm is divided by the volume expressed in cm^3, the dimension protons/cm^2 is obtained. Figure 3 explains the well-known fact that the angle of incidence in this dimensional definition is irrelevant since it merely changes the number of individual particles making up the total length, but not the total length itself. It is seen, then, that the total track length in a given volume, i.e., the total energy dissipation in it, depends only on the flux expressed in protons/cm^2 and on the magnitude of the volume, but not on a particular shape of the volume nor on the angles of incidence of the particles traversing it. Formally, it is admissible to visualize the flux expressed in protons/cm^2 as that of parallel beam of right angle incidence. As far as total track length and energy dissipation are

concerned, this transformation represents a completely equivalent system furnishing the absorbed dose correctly. As mentioned, these relationships have the practical consequence that measurements of absorbed dose and LET spectrum can be accomplished with a substantially simpler experimental design, i.e., with a smaller emulsion volume and simplified microscopic evaluation procedures, since analysis of the directional distribution of the particle flux can be dispensed with.

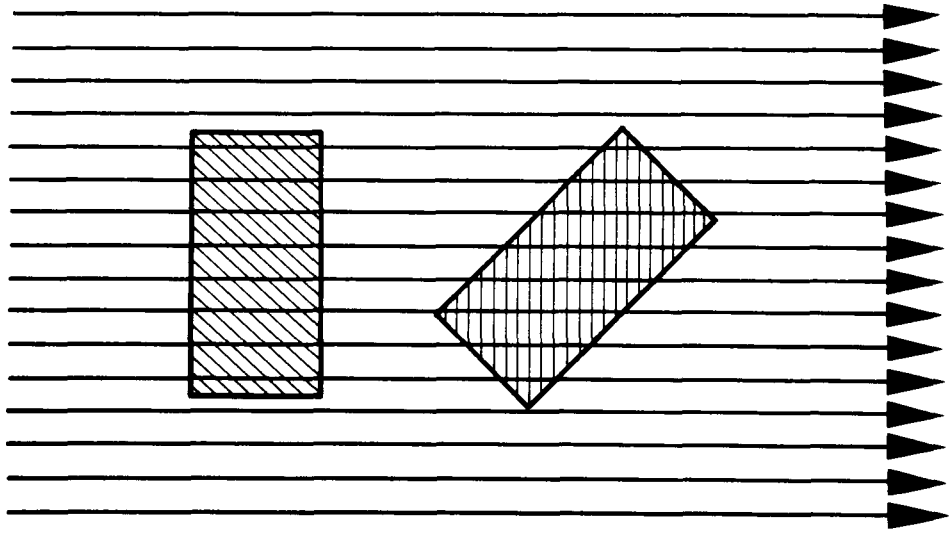

Figure 3

Total Track Length in a Given Volume for Different Angles of Incidence

Note that total track length depends only on flux density and volume, but not on angle of incidence. (Use ruler or apply simple trigonometry.)

DOSE AND DOSE EQUIVALENTS ON MA-9

It was pointed out above that the high LET fraction of a proton exposure can be expressed in two different ways. The conventional method would be to establish fractional ionization dosages for narrow intervals of the differential energy spectrum and to multiply these dosages by the corresponding RBE and QF factors to be obtained from the formula proposed by the RBE Committee of the ICRP (2). The alternate way

would be to establish the LET distribution from the differential energy spectrum and compare it to corresponding distributions of known types of radiations.

The results of the first method are presented in Figures 4, 5, and 6. Figure 4 shows the absorbed dose per Mev for the full energy range of Figure 1. The initial

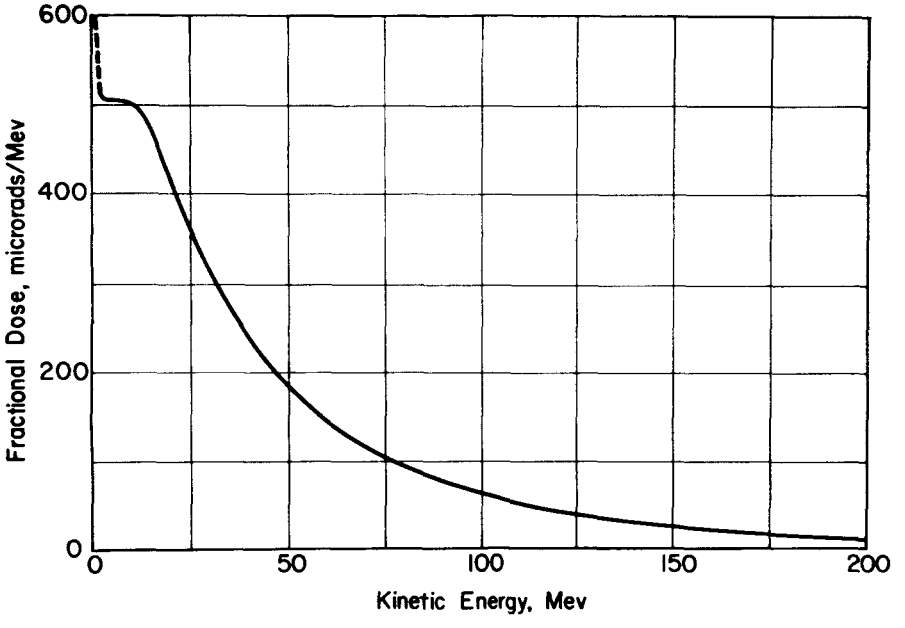

Figure 4

Fractional Absorbed Dose per Mev for Proton Exposure on MA-9

For higher resolved plot of left end section see upper graph in Figure 5.

section, in which the differential particle number shows a very steep rise, is shown separately, with a greatly expanded abscissa scale comprising the energy range from zero to 1 Mev, in the upper graph of Figure 5. In the lower graph of the same figure, RBE and QF as they follow from the formula of the ICRP (2) are plotted over the same abscissa scale. It is seen that the maximum of absorbed dose occurs in close vicinity of the corresponding maxima of RBE and QF. As a consequence, the products of absorbed dose and RBE or QF respectively, representing the RBE- and QF-dose equivalents, show more sharply peaked maxima as seen in Figure 6. In judging the relative contributions of different energy regions to total dose and total dose equivalents one should be aware of the fact that the fractional doses in Figures 4, 5, and 6 are plotted in millirads or millirems per Mev. This means that, for the greatly expanded abscissa scales in Figure 5 and 6, the contributions per unit abscissa interval, i.e., per 0.2 Mev, are only one fifth of the millirad or millirem amounts read from the curves. The fractional doses in the spectral region of greatly increased RBE and QF factors, thus, are actually quite small.

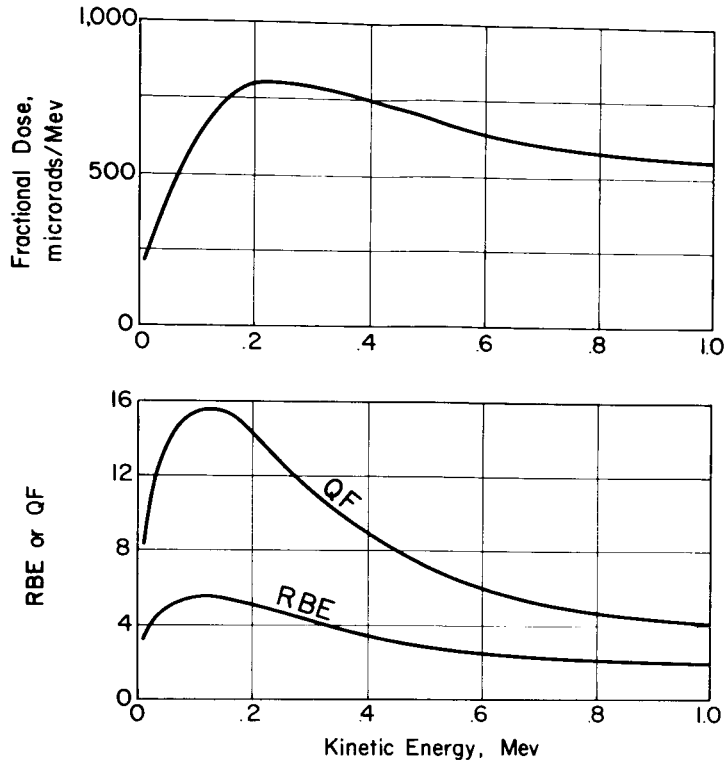

Figure 5

Fractional Absorbed Dose per Mev (Upper) and RBE and QF (Lower) at Low Energies

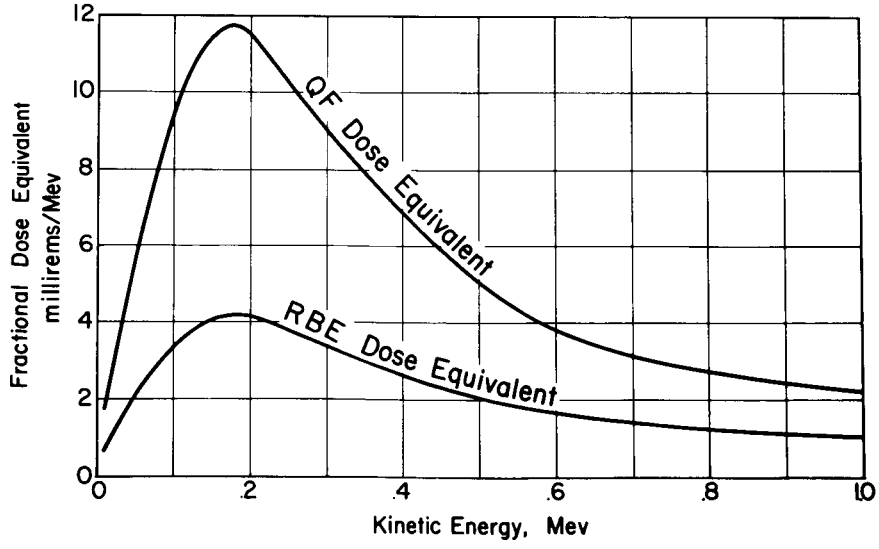

Figure 6

Fractional Dose Equivalents per Mev at Low Energies

Of special interest is the question of the accuracy with which the fractional dose equivalents in the low energy region are measured. This problem was discussed before when the implications of the steep rise of the differential energy spectrum in the region in question were investigated. Figure 5 demonstrates that large parts of the RBE- and QF-dose equivalents result from the energy region from zero to about 0.12 Mev. In this region the two factors to be multiplied by each other for obtaining the RBE or QF dose equivalents show a steep rise. The product, therefore, very sensitively depends on both the relative position of the steep flanks on the abscissa scale and on the steepness itself. A minor error in either parameter will appear greatly magnified in the product, i.e., in the fractional dose equivalents.

Quite aside from the just-explained mathematical reason for poor accuracy, it also must be pointed out that experimental data on the LET as a function of energy are scarce for the energy region in question, especially in the initial part up to 0.08 Mev. It is seen, then, that really all parameters involved, theoretical as well as experimental ones, act together in seriously limiting the accuracy of a separate assessment of the high LET fraction of the total dose.

It must be pointed out that the indicated error effect will make itself felt in any instrumentation or experimental design which would try to determine the high LET dose indirectly by establishing the energy spectrum from measurements of particle ranges. The difficulties in question would be avoided only with a device analyzing the local LET spectrum directly by measuring pulse height distribution. The ever present background of heavy nuclei and other pulse producing components of the ordinary cosmic ray beam, against which such a device would have to discriminate in actual operation in space, introduces another specification making the task more difficult.

LET SPECTRUM ON MA-9

Since the RBE of a radiation depends on the LET of its ionizing agents, analysis of the LET spectrum is a more direct way of defining radiation quality. It is also more precise inasmuch as it avoids entirely the problematic issue of the many biological parameters modifying the quantitative relationship between RBE and LET. The requirements for a complete quantitative analysis of the LET spectrum have been discussed in earlier reports (3, 6). Merely a brief summary of the basic principles will be given here.

The term LET in its common usage denotes the total energy which an ionizing particle dissipates per unit length of travel in absorbing material. For protons in particular, electrons play a complex role in the energy transfer from radiation to matter since they receive, in the primary collisions, individual energies that vary greatly, depending on the closeness of collision. The secondary electrons of first order resulting from primary collisions distribute their energies to secondaries of higher orders. For protons of kinetic energies of several Mev and beyond, some of the electrons receive enough energy to branch out from the path of the primary proton and to travel over

distances covering several or even many cell diameters in living tissue. It is seen, then, that if LET is quoted in the usual way by means of the total energy dissipation per micron path of the primary proton, no information is given on the actual tissue volume over which the energy is spread. In order to obtain such information, a separate follow-up of all secondaries involved would be necessary, ultimately furnishing a complex LET spectrum rather than a single LET value. It has become generally accepted to consider as local, in this type of LET analysis, an energy transfer of 100 e-volts or less from the proton or electron to tissue. That means the indicated breakdown of the energy dissipation has to be carried down to this energy level. For further details, the above-mentioned references (3, 6) should be consulted.

The lower graph in Figure 7 shows the LET spectrum of the proton spectrum of Figure 1 established in the indicated way in terms of local energy dissipation. For

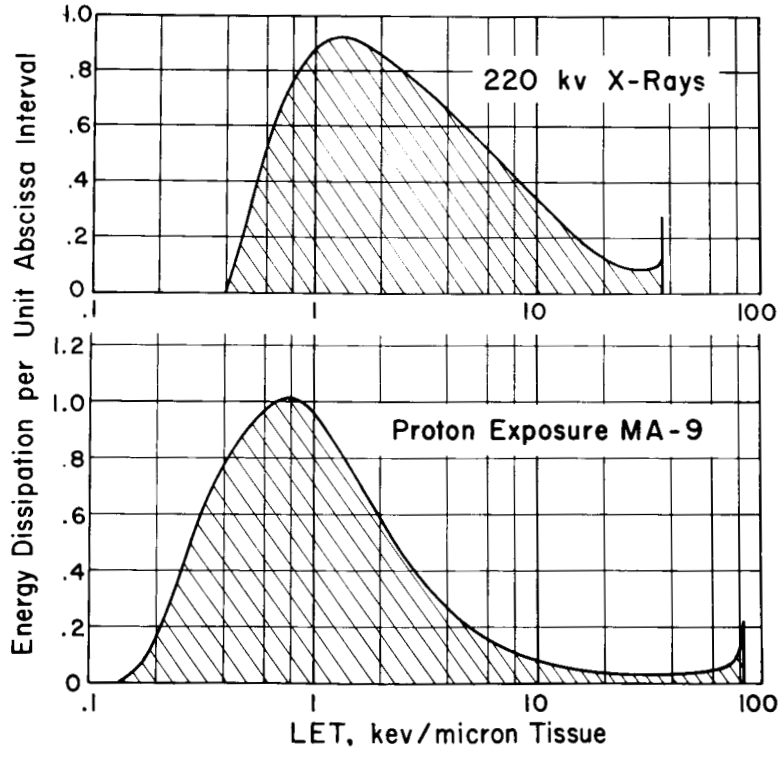

Figure 7

LET Spectra of Standard X-Rays (Upper) and of Proton Exposure on MA-9 (Lower)

comparison, the upper graph shows the corresponding spectrum for standard x-rays as communicated by Cormack and Johns (7). While the basic configurations of the two

spectra are quite similar, it is noteworthy that the MA-9 spectrum reaches farther out at both ends than the x-ray spectrum and that the maximum of the main part occurs, for the proton spectrum, at a lower LET than for the x-ray spectrum. The small, sharply pointed, second maximum at the upper end of the LET scale occurs, for the proton spectrum, at a considerably higher value than for the x-ray spectrum. This particular feature of the proton spectrum bears special significance inasmuch as the spectral section in question represents the basically different fraction of the total ionization which would have to be treated separately in assessing long-term damage. As pointed out above, the smallness of this fraction does not constitute sufficient justification in general for disregarding it since it is fully cumulative for repeated exposures over longer time spans, contrary to the bulk of the energy dissipation about the main maximum which has essentially the same quality as standard x-rays. In fact, a sizeable part of this main section reaches out farther to the left, well below the minimum LET of the x-ray spectrum. This section of the spectrum represents the local energy transfer in primary collisions of protons of 60 Mev and more, which are known to have a markedly lower biological effectiveness than standard x-rays (8). It would not seem an admissible proposition, however, to consider the two portions of excessively low and excessively high LET in the proton spectrum as compensating each other because the corresponding dose fractions differ basically in their respective recovery factors for assessing long-term damage.

DISCUSSION

If the significance of the present study with regard to dosimetric instrumentation for ionizing radiation in space is to be discussed in general, two implications of the findings are of special importance. Since the data pertain to the integral proton exposure of the astronaut on an actual orbital mission of thirty-five hour duration, it seems of interest to compare the resulting LET spectrum with that obtained earlier by evaluation of energy spectra of protons recorded on instrumented balloon and rocket flights (9). It is very reassuring that the spectrum reported here for MA-9 very closely resembles the earlier ones. This seems to indicate that one and a half tons of compact material of a Mercury capsule does not produce enough secondary protons in nuclear interactions to alter significantly the low energy section of the differential energy spectrum. The configuration of the energy spectrum on MA-9 clearly indicates that spectral degradation is mainly, if not exclusively, produced by ordinary ionization with nuclear interactions contributing, if at all, only insignificantly to it. In regard to the limitation of the present study to the proton component, it should be pointed out that the additional exposure on MA-9 from all other components is estimated at 2 millirads, i.e., at slightly less than 7.5 per cent of the proton exposure (1).

The second implication of the findings reported here concerns the design of suitable instrumentation for measuring the absorbed dose from the proton component. As pointed out repeatedly in the preceding sections, the high LET portion of this dose needs to be measured or determined separately for radiobiological reasons. Quite obviously, on missions for which the exposure might reach objectionable levels such

measurements could not be carried out with passive dosimeters such as nuclear emulsions. Direct reading doseratemeters would be needed instead. It would seem a simple method for such instrumentation to measure the high LET dose fraction with an absorption spectrometer technique, identifying the low energy fraction of the flux by its low range. This, however, would again introduce the same basic inadequacy of poorly resolving the terminal sections of the proton tracks which are the exclusive contributors to the dose fraction in question. What methods or devices might exist for measuring the energy dissipation in the terminal "spikes" of proton enders directly and separately seems a difficult question. It anyway is not within the scope of this study.

In this connection, it might be mentioned that energy spectra of protons in space radiation studies are usually established from data that ultimately derive from measurements of residual ranges. Therefore, they carry essentially the same increased error margin at the low end of the energy spectrum. While such proton spectra are entirely satisfactory for a quantitative assessment of the total tissue ionization dose in a human target even for a degraded spectrum behind heavy shielding, the small fraction of this total dose produced at high LET, i.e., by enders, is only very poorly defined. The problem grows more complicated at energies in the multihundred million e-volt range and beyond in which nuclear collision becomes a competing and finally the predominant attenuation process. Under these conditions, locally produced, low energy, secondary protons start contributing to the local enders count. For the particular energy spectrum under discussion, however, as well as for most flare produced proton beams in general, the bulk of the particle flux is contained in the spectral region below 200 Mev. At these energies, attenuation due to ordinary ionization by far outweighs nuclear collision, and the number of locally generated secondary protons remains insignificant (10).

The peculiar difficulties encountered in measuring the high LET portion of the total dose for continuous proton spectra, which have been discussed at length above, are of interest exclusively from a radiobiological standpoint. In years past when interest in satellite experimentation centered on the physical parameters of proton radiation fields in space, these radiobiological aspects were not of practical importance. As the need now arises for measuring the astronaut's exposure directly, instrumentation has to meet new and different specifications.

REFERENCES

1. Schaefer, H. J., and Sullivan, J. J., Measurements of the astronauts' radiation exposure with nuclear emulsion on Mercury Missions MA-8 and MA-9. BuMed Project MR005.13-1002 Subtask 1, Report No. 27 and NASA Manned Spacecraft Center. Pensacola, Fla.: Naval School of Aviation Medicine, 1964.

2. Report of the RBE Committee to the International Commissions on Radiological Protection and on Radiological Units and Measurements. Health Physics, 9: 357-384, 1963.

3. Schaefer, H. J., LET analysis of tissue ionization dosages for proton radiations in space. BuMed Project MR005.13-1002 Subtask 1, Report No. 21. Pensacola, Fla.: Naval School of Aviation Medicine, 1962.

4. NASA Life Sciences Data Book. First Ed. Contract NASr-89. Yellow Springs, Ohio: Webb Associates, 1962.

5. Ney, E. P., and Stein, W. A., Solar protons, alpha particles, and heavy nuclei in November 1960. J. Geophys. Res., 67:2087-2105, 1962.

6. Schaefer, H. J., Energy dissipation characteristics in tissue for proton radiation in space. I. Comparative analysis of the LET spectra of monoenergetic, flare produced, and fission neutron recoil protons. BuMed Project MR005.13-1002 Subtask 1, Report No. 24 and NASA Order No. R-75. Pensacola, Fla.: Naval School of Aviation Medicine, 1963.

7. Cormack, D. V., and Johns, H. E., Electron energies and ion densities in water, irradiated with 200 keV, 1 MeV and 25 MeV radiation. Brit. J. Radiol., 25: 369-381, 1952.

8. Wang, C. C., Lyman, J., and Tobias, C. A., Relative biological effectiveness of 730-Mev proton particles for acute lethality of mice. In: Lawrence, J. H. (Ed.), Biology and Medicine Semi-Annual Report. UCRL-10211, Berkeley, Calif.: U. of Calif., Radiation Lab., 1962. Pp 43-49.

9. Schaefer, H. J., Local LET spectra in tissue for solar flare protons in space and for neutron-produced recoil protons. In: Biological Effects of Neutron and Proton Irradiations. Vol. I. Vienna: International Atomic Energy Agency, 1964. Pp 297-306.

10. Schaefer, H. J., A note on the influence of nuclear collision on the radiation dose from flare produced protons in space. BuMed Project MR005.13-1002 Subtask 1, Report No. 23. Pensacola, Fla.: Naval School of Aviation Medicine, 1962.